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# TYPHOON INTERACTION WITH THE TAIWAN TOPOGRAPHY DURING THE TROPICAL CYCLONE STRUCTURE - 2008 (TCS-08) EXPERIMENT

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## 1. INTRODUCTION

The importance of accurate typhoon forecasts to the island of Taiwan and the existing challenges in this area are reviewed by Wu and Kuo (1999). A particular area of emphasis is understanding the physical processes resulting from the interaction between typhoons and the Central Mountain Range, which runs across the center of the island. Wu and Kuo (1999) discuss much of the earlier research in this area, but additional work has continued to be done in the last decade with an increasing focus on the resulting precipitation distributions over the island. While idealized studies such as Lin et al. (2005) have been important in clarifying the basic theory of cyclone-terrain interaction, case studies of actual events continue to be necessary to apply these theoretical ideas to real storms.

The island of Taiwan was located within the study area of the Tropical Cyclone Structure - 2008 (TCS08) experiment which was carried out in August and September of 2008 in the western North Pacific. During the course of the TCS08, two storms made landfall on Taiwan: Typhoon Sinlaku in mid-September and Typhoon Jangmi two weeks later. These storms were both distinguished by especially large maximum rainfall accumulations, particularly in the case of Sinlaku. In this study, we will examine the effect of the Taiwan terrain on the track and precipitation distribution of these two storms using real-data numerical model simulations. We will also present preliminary model results from Typhoon Morakot which struck Taiwan a year after TCS08 and produced as much rainfall as Sinlaku and Jangmi combined.

## 2. MODEL SETUP

Numerical simulations for these events were performed using a special version of the Naval Research Laboratory's Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS®) designed specifically for forecasting tropical cyclones (COAMPS-TC). The core numerics in COAMPS-TC is the same as in the parent model. The equations are incompressible and nonhydrostatic and are solved on an Arakawa-C grid with a terrain-following vertical coordinate system. Parameterizations schemes for turbulence, radiative transfer, cumulus convection, and microphysics are used for coarser grid resolutions. The lateral boundary conditions for the coarse domain are provided by forecasts from the Navy Operational Global Atmospheric Prediction System (NOGAPS), while the initial conditions are output from a 3DVAR scheme called NAVDAS which can use either NOGAPS or COAMPS as a first guess field.

In addition to more sophisticated microphysics and the inclusion of sea spray processes, COAMPS-TC also benefits from a moving nest system which tracks the center of mass of tropical cyclones which have been identified in operational warning messages. This tracker is independent of the output track data which uses the center of circulation. In these simulations, we use a horizontal resolution of 45 km in the outer domain and 15 and 5 km in the two moving domains. Cumulus parameterization is used in the two outer domains, while explicit microphysics is used in the finest mesh. The typhoons are initialized using synthetic observations based on the operational warning messages. The wind field formed by these bogus observations is asymmetric and has the same maximum wind speed and wind speed radii as the actual storm. In order to initialize an intense storm, a strong vortex must already be present in the first guess field. To this end, we ran an update cycle consisting of 12-hour forecasts from shortly after formation of each typhoon until they began to approach Taiwan. These previous COAMPS-TC forecasts were used to initialize a 72-hour control simulation.

In order to determine the effect of the orography of Taiwan, a series of sensitivity experiments were performed for each case in which the terrain of the island was reduced and ultimately eliminated. The terrain was only modified prior to the 72-hour control simulation resulting in the sigma surfaces being appropriately lowered in elevation. Runs were also performed with the island replaced by open ocean as opposed to flat land to determine the relative importance of orography and the land-sea contrast.

## 3. TYPHOON SINLAKU

The fifteenth tropical depression of the 2008 typhoon season developed from a cloud cluster east of the Phillipines at 12 UTC 8 Sep 2008. It quickly intensified through tropical storm strength into a typhoon within 24 hours. At this point, the storm moved in a northerly direction until 00 UTC 12 Sep when it suddenly made a sharp turn to the left and moved toward the northern tip of Taiwan. Prior to this change in direction, the typhoon had increased to category four strength. Landfall occurred

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at 18 UTC 13 Sep, but Sinlaku quickly moved back offshore making a small cyclonic loop before passing over the northern end of the island. After the storm moved back over water, it immediately began recurving to the northwest and continued toward Japan, where it reintensified again before eventually transitioning into an extratropical cyclone.

In addition to being an intense storm capable of producing strong upslope motion along the western slopes of the Central Mountain Range (due to its location over the northern part of the island), the translational speed of Sinlaku was lower than average resulting in longer durations of heavy orographic precipitation. The end result was record rainfall at many locations. The highest observed total was 1611 mm (63.43 in), but many locations received in excess of 1000 mm. The resulting flooding resulted in the collapse of a road tunnel, three bridges, and two hotels, with $22 million dollars damage to agricultural industries alone.

### 3.1 *Control Simulation*

Figure 1 compares the COAMPS-TC forecast track for Sinlaku with the JTWC best track. For the first 12-18 hours, the model correctly predicts the storms direction of movement albeit with a noticeable slow along-track bias. As the simulated storm get closer to the island, it begins to experience a southward deflection and eventually makes a small cyclonic loop before making landfall and moving back to the north. The looping motion matches the behavior seen in the actual storm, but the southward deflection seen in the model did not occur in reality. After passing over the island, both the observed and simulated storm began an immediate recurvature process that agrees quite well. (Since the model tracker follows the center of circulation, the loop off o the western coast may be due to the land surface distorting the weaker flow field as opposed to the actual motion of the simulated storm.)

Lin et al. (2005) showed that southward deflection upstream of an island barrier is favored when the tropical cyclone is weak or has a small radius in comparison to the width of the island. According to the JTWC best track data, Typhoon Sinlaku had a maximum sustained wind speed of 100 knots and a gale-force wind radius of 140 nm in the smallest quadrant at 00 UTC 13 Sep. While the NAVDAS analysis initialized the model storm to match these values, twelve hours of forecast time resulted in a maximum wind speed of 65-70 knots and a gale-force wind radius of 110 nm in the largest quadrant. Thus, the model storm has contracted and weakened after initialization making it more prone to being deflected to the south when it nears the island. This characteristic of the model has also been investigated in an idealized framework (see companion paper **9.6**).

The relatively small ($<$ 65 km) track error has important consequences for the QPF forecast. Figure 2 shows the QPF error for the total accumulation during the simulation period. While the rainfall is predicted well at a large number of points, there are individual stations where the rainfall total is overpredicted or underpredicted by close to or over 1000 mm. Note that some of the largest values are located in the area between the best track and the forecast track. While during the actual storm the windward side of the mountains was to the west and the leeward side was to the east, in the model this is reversed resulting in the extreme differences in rainfall seen here. Other areas of significant underprediction along the western slopes of the mountains are likely due to the smaller and weaker circulation associated with the model storm as described earlier.

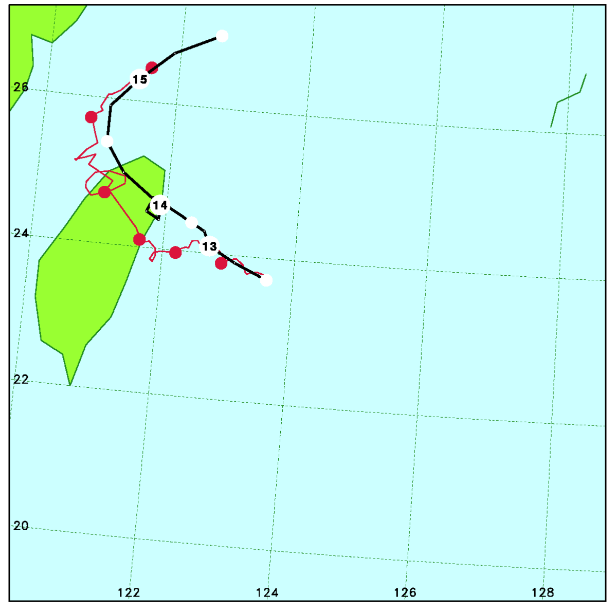


FIG. 1: JTWC best track (black) and COAMPS-TC forecast track (red) for Typhoon Sinlaku from 12 UTC 12 Sep - 12 UTC 15 Sep 2008.

### 3.2 *Sensitivity Experiments*

When the elevation of the Taiwan terrain in the model simulation is reduced to 75% of its actual elevation, the resulting track is very similar to the control run for the first 24 hours (Fig. 3). However, after deflecting to the south for a small distance, the storm quickly turns to the NNW and subsequently makes landfall on the island very close to the point observed in the best track simulation. This results in a significantly improved QPF forecast compared to the control simulation. It appears that the slightly lower terrain results in a southward deflection of lower magnitude than what occurs with the real orography.

When the terrain elevation is reduced to 50% (not shown), the amount of deflection is reduced even further. Ultimately, when the elevation over the entire island is set to 0 m (Fig. 3), this southward deviation is eliminated entirely. After moving in a WNW direction for the first 12 hours (with an improved along-track bias), the storm turns to a more northwesterly direction, similar to

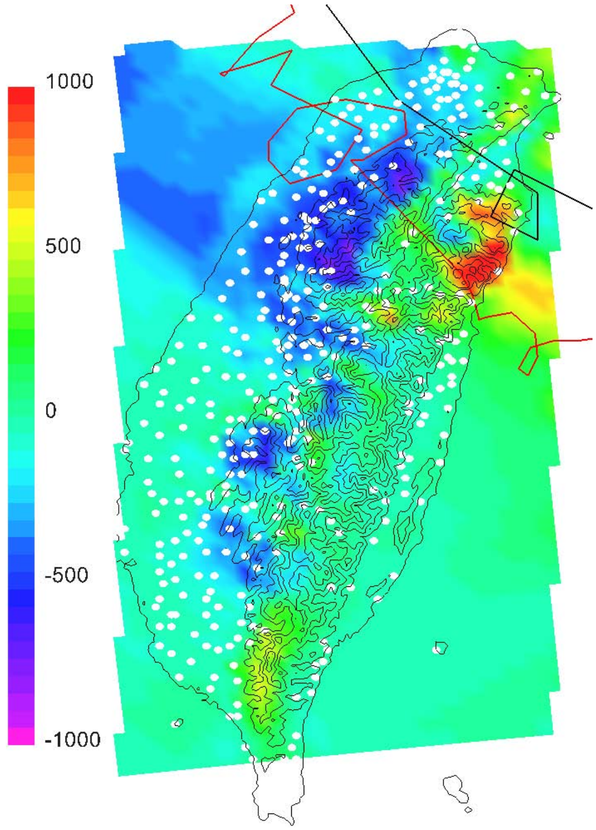


FIG. 2: Difference between 72-hour accumulated rainfall from objective analysis of rain gauge observations and COAMPS-TC forecast (shaded) and terrain elevation (contoured - 500 m).

the best track. The storm continues to turn to the right resulting in a recurvature that occurs upstream of the island. This is in contrast to both the control simulation and the actual track where recurvature only began after the typhoon had passed over the island. This suggests that the role of the topography in this case is to delay the recurvature process and result in the storm making landfall when it would not have otherwise. This process illustrates another terrain-induced effect on the precipitation pattern, since pre-existing convective precipitation associated with Sinlaku could still produce significant rainfall without upslope forcing, but does not due to the modifications in the storm track. Results in which Taiwan is replaced by ocean are nearly identical to the 0% terrain simulation indicating that orography is more important than the land-sea contrast in this case.

### 4. TYPHOON JANGMI

Shortly after Sinlaku was reclassified as an extratropical system, the nineteenth tropical depression of the season formed over 2500 km to the SSW. Less than 12 hours later, Typhoon Jangmi had become a named storm and was moving in a NW direction toward Taiwan. Jangmi

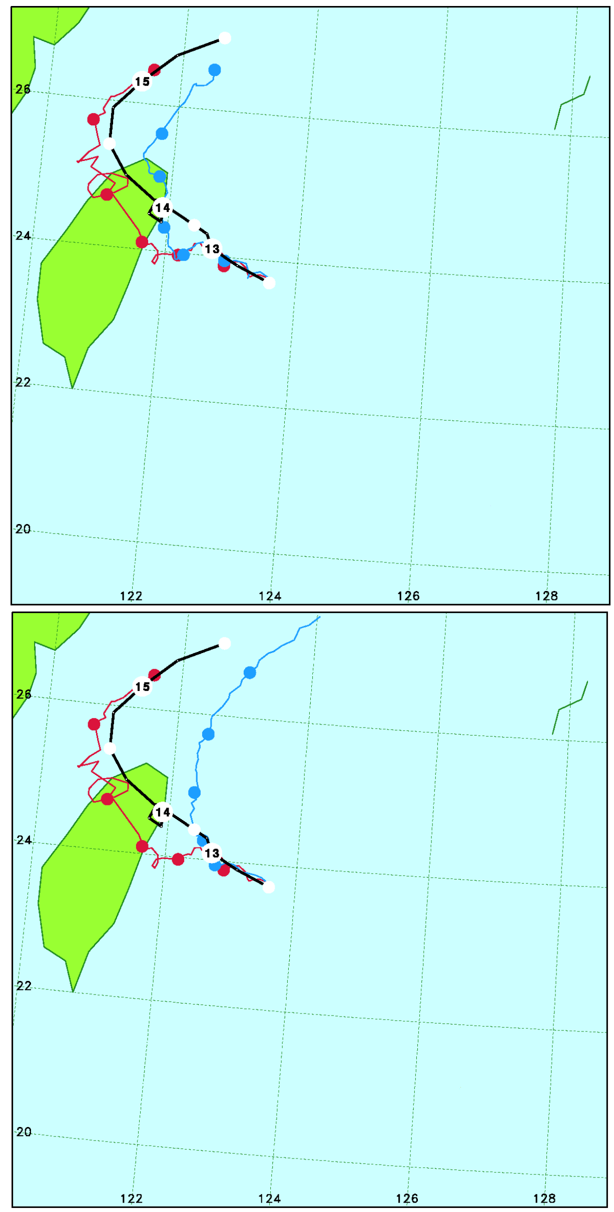


FIG. 3: Same as in Fig. 1, but with COAMPS-TC sensitivity run (blue) for (top) 75% and (bottom) 0% terrain elevation.

would eventually strengthen into a borderline category five storm, but weakened before reaching Taiwan when it crossed over the cold ocean wake left over from Sinlaku. However, the typhoon still contained maximum winds in excess of 110 knots as it approached the island. Radar imagery from Taiwan seems to indicate that the track of Typhoon Jangmi was similar to Sinlaku with cyclonic loop being made after landfall. However, the landfall point was further south than it had been for the previous storm.

Jangmi was a significantly faster moving storm than Sinlaku and consequently, the rainfall totals were lower over most locations. However, there were favored areas that experienced strong upslope flow resulting in extreme local values, such as 1125 mm (44.29 in) at Taiping Mountain. Since Jangmi was also a stronger storm than Sinlaku, higher surface wind gusts were observed over the island, up to 139.5 knots. This factor along with the already saturated land surface again lead to a large amount of property damage.

### 4.1 *Control Simulation*

When the control simulation for Jangmi was initialized at 12 UTC 27 Sep, the track of the model typhoon was significantly to the left of the best track during the first several hours. Possibly, this is due to initializing the storm over the cold SST wake left over by Typhoon Sinlaku, for which a coupled simulation would be more suitable. When the control simulation is started at 00 UTC 27 Sep, the results are significantly improved as shown in Fig. 4. The simulated storm follows the best track in a northwesterly direction before making a slight turn to the right at 12-24 hours, although there is again a slow along-track bias in the model. When the storm begins to approach the Taiwan coastline, the simulation again contains a significant southward deviation that is seen in the best track as only a small cyclonic loop. The size of Jangmi in the model actually agrees fairly well with the best track values, but the intensity is again over 20 knots to weak, which may explain the excessive deflection The model storm exits the island along the middle western coastline as opposed to the northern tip of the island and continues to linger in the Taiwan Strait.

Figure 5 shows the QPF error for the COAMPS-TC forecast of Jangmi. It is important to note in this figure that observations are not available in several areas where the model is producing very large precipitation amounts. Therefore, some of the largest differences may not be errors at all. Despite the model track again being south of the observed storm, the QPF errors are significantly lower in this case, especially the region that exhibited large overprediction in the case of Sinlaku. This is probably a combination of the model track being further south for Jangmi and the storm moving faster in this case. One of the largest errors is in a concave region in the west-central slopes of the Central Mountain Range which was exposed to persistent westerlies during the actual event, but was located near the storm's eye in the simulation.

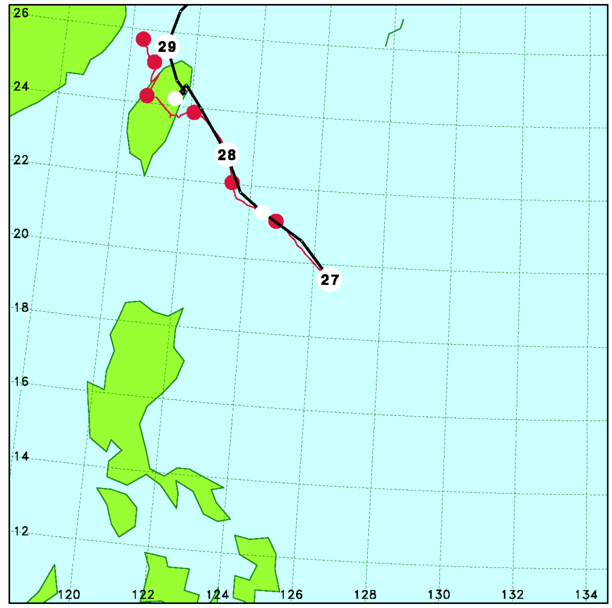


FIG. 4: Same as in Fig. 1, but for Typhoon Jangmi from 00 UTC 27 Sep - 00 UTC 30 Sep 2008.

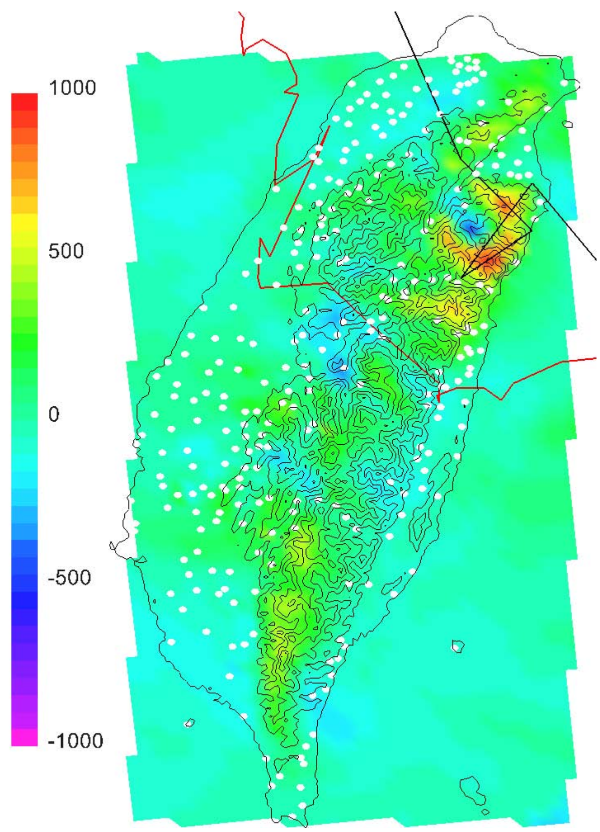


FIG. 5: Same as in Fig. 2, but for Typhoon Jangmi.

### 4.2 *Sensitivity Experiments*

When the terrain of Taiwan is reduced to 75% its actual height, the track of Jangmi remains similar to that seen in the control simulation, but the turn to the right upstream of Taiwan is not as sharp as in the previous run or in the best track (Fig. 6). In the sensitivity test, the typhoon also begins to turn to a more westerly direction before making landfall. However, unlike the control simulation, there is very little southerly movement directly upstream of the island and the storm with 75% terrain makes landfall very near to the storm in the control simulation, both to the south of the observed location.

The sensitivity test with 50% terrain (not shown) is very similar to the run in which the mountains have been removed (Fig. 6). There is no longer any deviation in track upstream of the island. Instead, the model typhoon continues to move in the same direction as at the beginning of the simulation until landfall occurs. These results suggest that the observed shift from a NW heading to a NNW heading is caused by the orography of Taiwan. This results in a landfall point further to the north and also causes some of the strongest flow around the north side of the storm to move over open ocean instead of impacting on the east side of the Central Mountain Range except in the far northeast corner of the island. Consequently, precipitation totals at some locations along the western mountain slopes are actually reduced when high, as opposed to moderate topography, is present.

## 5. TYPHOON MORAKOT

While both of the TCS-08 storms that struck Taiwan produced heavy rainfall and widespread damage, their societal impact was dwarfed the next year by the effects of Typhoon Morakot. Morakot developed out of a large-scale monsoon gyre (Ge et al. 2010) reaching tropical depression strength shortly after 18 UTC on 3 Aug 2009. The system quickly deepened to tropical storm strength and began moving in a westward direction toward Taiwan. Prior to making landfall, Morakot only intensified slightly, falling just below category two status, but it maintained an unusually large eye (Ge et al. 2010). Despite its low intensity, the typhoon shattered rainfall records over the island, in large part due to the convergence of its own circulation with a southwesterly monsoon jet directed toward the southern end of the island (Hong et al. 2010). The converging airflow was also directed toward the slopes of the Central Mountain Range resulting in additional upslope forcing. Finally, similar to Typhoon Sinlaku, Morakot had a low translational speed which resulted in heavy rainfall persisting over a longer time.

At the village of Alishan, the accumulated rainfall for 7-10 Aug was 2965 mm (116.73 in) with 2327 mm (91.61 in) falling just on 8-9 Aug, very nearly setting a world record. As a result, flooding and landslides were widespread across the southern part of the island. The collapse of the six-story Jinshuai Hotel was captured on film and broadcast by the international news media. In

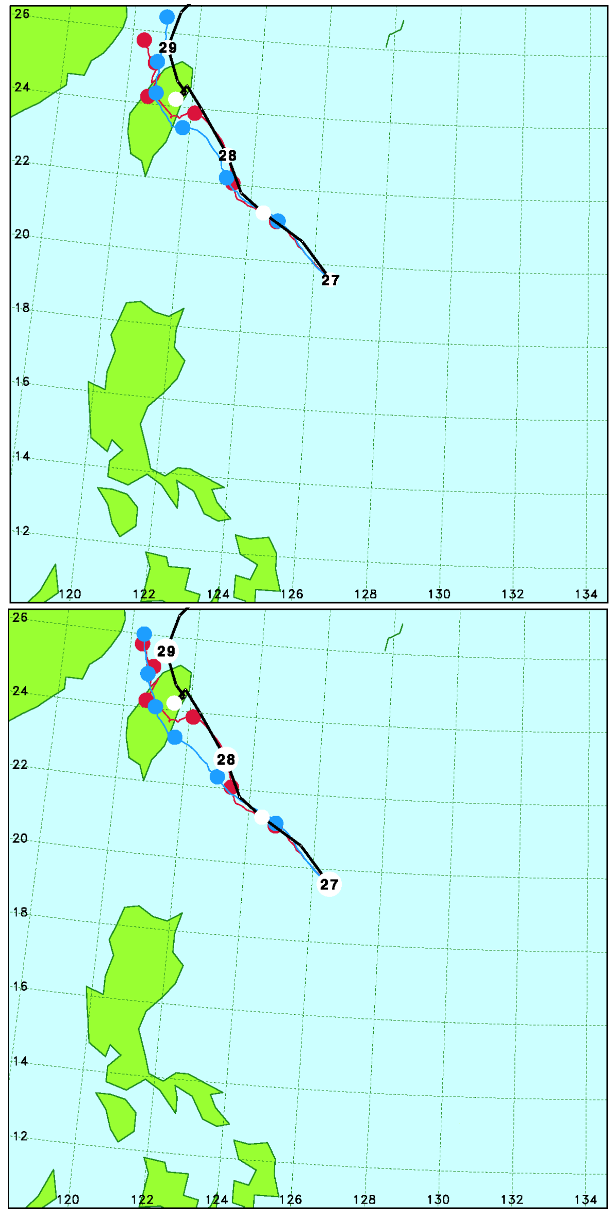


FIG. 6: Same as in Fig. 4, but with COAMPS-TC sensitivity run (blue) for (top) 75% and (bottom) 0% terrain elevation.

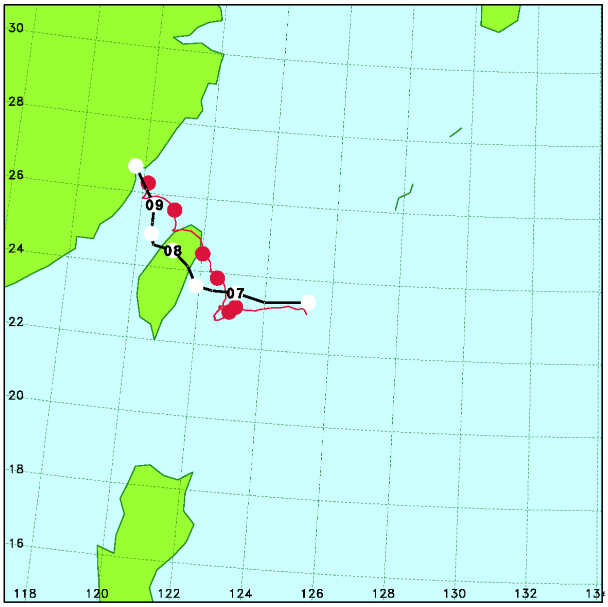


FIG. 7: Same as in Fig. 1, but for Typhoon Morakot from 12 UTC 6 Sep - 12 UTC 9 Sep 2009.

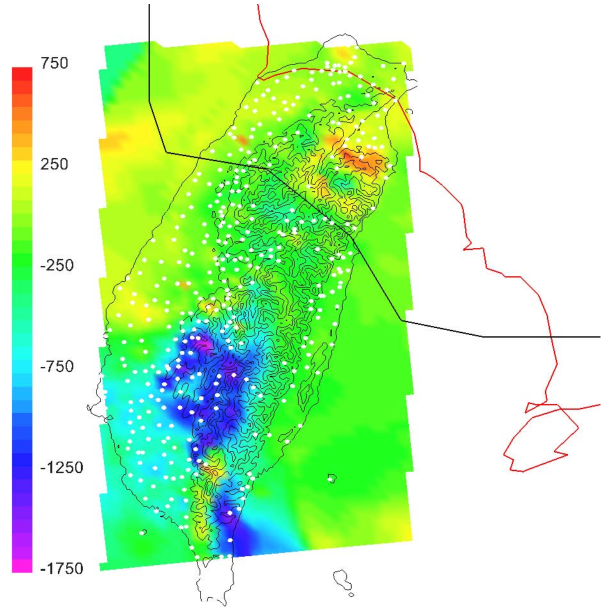


FIG. 8: Same as in Fig. 2, but for Typhoon Morakot.

the most catastrophic incident, the entire village of Xiaolin was buried by a large landslide, killing over 100 people. In total, the storm resulted in nearly 700 people killed or missing and approximately $4.7 billion USD in damage (Ge et al. 2010) making it the worst disaster to strike Taiwan in 50 years.

Figure 7 shows the COAMPS-TC forecast track for Morakot. The model storm moves toward Taiwan in a westerly direction for the first twelve hours, but subsequently deflects slightly southward and stalls off the coast for another twelve hours. When the simulated typhoon begins to move again it is in a NNW direction with landfall eventually occurring at the northern end of the island. While the initial movement and the location of the storm after passing over Taiwan agrees well with observations, the lingering upstream and northward deflection are not features of the JTWC best track. However, it should be noted that there is considerable disagreement between the best tracks of the various warning agencies for this storm.

The northward displacement of Morakot's track likely played a large role in the QPF errors seen in Fig. 8. Some rainfall totals in the northern part of the island are overpredicted by over 500 mm while the largest totals in southern Taiwan are underforecasted by close to 1750 mm. However, other factors need to be evaluated, such as the accuracy of the monsoonal jet forecast, to determine how much of this error is due to the track and how much is related to larger scale features or other mechanisms.

Figure 9 shows the results of the sensitivity run in which the mountains of Taiwan have been removed. Unlike the cases of Sinlaku and Jangmi, there is little significant difference between the sensitivity run and the control simulation until late in the forecast period when Morakot is already moving away from the island. These results are similar to those obtained by Ge et al. (2010) using WRF-ARW. The reason for the lack of terrain influence in this case still requires investigation, but may be related to larger instability associated with the environment in which Morakot formed. While the orography seems to have had little impact on the track, the precipitation is dramatically reduced without the terrain to the extent that there are no accumulations greater than 375 mm over the island.

## 6. SUMMARY AND CONCLUSIONS

For Typhoon Sinlaku, the effect of the Taiwan orography appears to be to delay the recurvature process and cause the storm to make landfall when it would not have otherwise. This results in greatly increased precipitation due to both convection in the eyewall and rainbands passing over the island and the airflow around the storm impinging on the western slopes of the Central Mountain Range. In the case of Typhoon Jangmi, the mountains cause a northward deflection far upstream of the island resulting in a different landfall point and easterly, upslope flow affecting less of the eastern coast. Preliminary results for Typhoon Morakot suggest that the terrain was a less significant factor in determining the storm's track, but was very significant in causing the extremely high rainfall totals. However, more investigation is needed for this event.

These simulations demonstrate the importance of accurately simulating the intensity and size of tropical cyclones. The control simulations of Sinlaku and Jangmi both contain southward deflections immediately

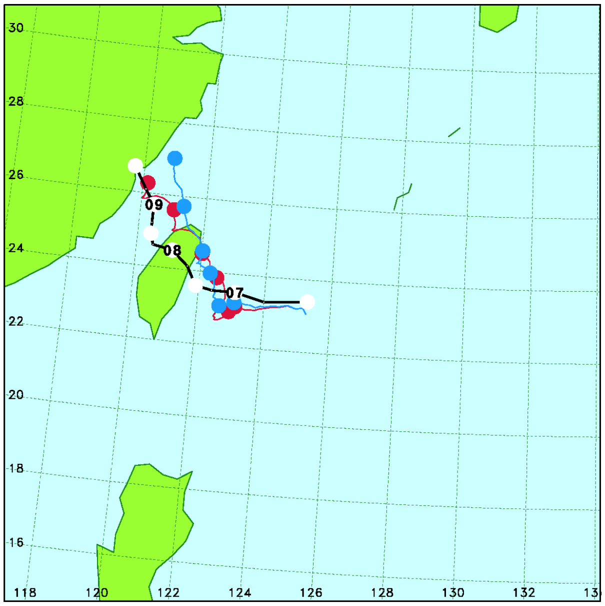


FIG. 9: Same as in Fig. 7, but with COAMPS-TC sensitivity run (blue) for 0% terrain elevation.

upstream of the island that are not observed in the best tracks. Consistent with the results of Lin et al. (2005), this could be due to the fact that the model Sinlaku is too weak and small and the model Jangmi is too weak. In the case of Sinlaku, this relatively small track error results in a very large error in the QPF forecast. Precipitation forecasts are also complicated by the highly non-linear processes involved. Modifications to the track caused by the terrain will relocate the circulation of the storm which determines the effects of orographic enhancement and suppression.

In addition to continuing with the parallel idealized numerical simulations and examining additional typhoons impacting other islands, future work will involve more precise diagnoses of the contribution of terrain versus storm-scale versus large scale effects in determining the rainfall totals. The sensitivity of the rainfall accumulation to the differences in track could also be determined more elegantly using an analytical or ensemble model. Another potential impact of typhoon-terrain interaction is the enhancement of leeside surface winds, which will be examined in these simulations as well as in an idealized framework. Finally, since the effects of heavy rainfall are usually manifested through surface flooding, coupling with a hydrological model could have more value in applying these results to forecast improvement.

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## REFERENCES

Ge, X., T. Li, S. Zhang, and M. Peng, 2010: What causes the extremely heavy rainfall in Taiwan during Typhoon Morakot (2009)? *Atmos. Sci. Lett.,* **11,** 46-50.

Hong, C.-C., M.-Y. Lee, H.-H. Hsu, and J.-L. Kuo, 2010: Role of submonthly disturbance and 40-50 day ISO on the extreme rainfall event associated with Typhoon Morakot (2009) in Southern Taiwan. *Geophys. Res. Lett.,* **37,** 6 pp.

Lin, Y.-L., S.-Y. Chen, C. M. Hill, and C.-Y. Huang, 2005: Control parameters for the influences of a mesoscale mountain range on cyclone track continuity and deflection. *J. Atmos. Sci.,* **62,** 1849-1866.

Wu, C.-C., and Y.-H. Kuo, 1999: Typhoons affecting Taiwan: Current understanding and future challenges. *Bull. Amer. Meteor. Soc.,* **80,** 67-80.